Core Sampler Evaluation Using the Finite Element Method

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ABSTRACT

ANSYS® *, a finite element program, was used to model soil deformation to determine how to minimize compaction of soil core samples used for bulk density measurements. An augered and a pushed soil core sampler were simulated with this method. The soil was modeled as a nonlinear plastic material with a certain sliding resistance on the metal sampler surface. Laboratory tests were conducted to verify the finite element results. The finite element method reasonably modeled the sampling process except in cases of excessive soil shear. Results indicated that an augered soil sampler minimized disturbance of the soil sample.

INTRODUCTION

Core samplers for a long time have been the standard device used to obtain bulk density measurements. They have shortcomings, however. As core samplers are pushed into the ground, they tend to compress the soil core (Wells, 1959). As a result, bulk density values obtained are erroneously large. Augers have been designed and attached to core samplers to minimize this compaction effect on the sample (Buchele, 1961), but their effect is questionable. It is possible that they might disturb the soil column, from their rotary action and associated vibrations, more than if the sampler was simply pushed into the soil.

Another source of soil sample compression comes from the frictional force that develops as the soil column slides by the sampler tip. Excess soil is trimmed away at this point, leaving a sample with the same outside diameter as the inside diameter of the soil sampler. Reducing the coefficient of friction between the soil and the sampler could reduce the amount of compression of the sample but also could make it difficult to remove the sample from the sampling hole. It seems that a small frictional force is necessary to hold the soil column inside the sampler (Fig. 1).

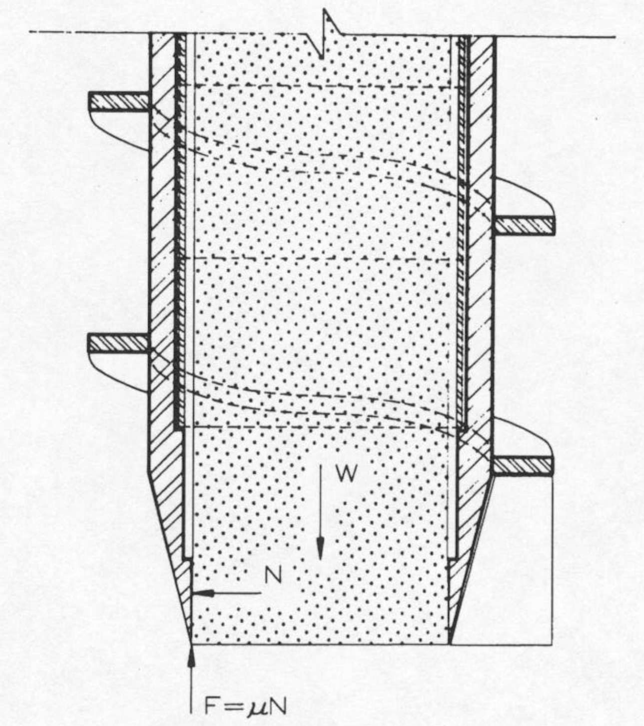

Fig. 1—Cross-sectional view of augered soil sampler, showing frictional force necessary to remove soil sample from ground.

Factors that could cause compression of a soil sample are difficult to investigate. In addition, direct observation of the compressive action of the soil sampler is not possible. For these reasons, a finite element solution was attempted. If the soil-soil sampler interaction could be modeled accurately, perhaps some helpful insight might be gained into this problem and some modifications made to increase the accuracy of bulk density measurements obtained with core samplers.

The objectives of this research were to:

1. Develop or implement the finite element method to effectively model soil deformation.
2. Use the finite element method to investigate the effect of an auger on soil core compaction.
3. Use the finite element method to investigate the effect of the soil-soil sampler frictional force on soil core compaction.

MATERIALS AND METHODS

Soil is a very complex material to model. The solid fraction of soil consists of extremely small clay particles positioned randomly between larger sand and silt particles. The soil structure varies spatially as well as

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with time. To simplify the finite element model, the following assumption was used: soil was assumed to be a homogeneous, isotropic, and layered medium. This assumption did not adequately describe the entire soil structure, but gave a basis for defining its mechanical properties.

Theoretical Considerations

ANSYS® (Desalvo and Swanson, 1983) is a finite element computer package that is widely used in industry for structural analysis of mechanical systems. It is capable of modeling various types of systems, incorporating many forms of elements into a finite element solution. ANSYS® was selected because it has the capability of modeling elastic-plastic behavior and also frictional behavior between different materials.

A nonlinear static analysis was used to investigate the effects of material plasticity and the frictional forces generated by the frictional slider element. With the program ANSYS®, the elastic-plastic constitutive law exhibited by soil was modeled by specifying five points for the stress-strain curve. Linear interpolation was used between these points to estimate the corresponding value of strain for the calculated value of stress.

ANSYS® also contains a frictional interface element (STIF12) that allows Coulomb friction behavior. After the necessary static frictional force has been overcome, yielding of the interface element takes place. The amount of yielding and the resulting frictional force depends upon the applied normal force and the coefficient of friction enabled lubrication of the soil core sampler tip to be evaluated.

This frictional interface element was used to model the effect of the core sampler tip on the soil column. This element enabled the sampler to be slid past the soil column so that the effect of the frictional force on the soil sample could be evaluated. If large frictional forces were present, the soil column would be deformed by an excessive amount. The coefficient of friction could ideally be reduced to find an optimum value that would eliminate soil core compaction, yet this same coefficient would be sufficient to keep the sample inside the soil sampler until it could be removed from the ground.

The soil core was modeled by using axisymmetric approach using linear elements (STIF42). The entire soil sample had a radius of 3.81 cm and was 20.32 cm in length. The vertical centerline of the core was taken to be where the radial distance "r" was equal to 0 cm, and the soil surface was assumed to be where the vertical distance "z" was equal to 0 cm. Fig. 2 shows finite element meshes of the first quadrants of the undeformed soil cores. Fig. 2a is the situation when an auger is used with a core sampler. The soil surrounding the soil sample was removed by the auger. Fig. 2b modeled the case when a core sampler is pushed into the ground deforming the soil that surrounds the soil sample.

A relatively small radial area of soil outside the soil sampler (3.81 cm) was modeled elasticly because of two reasons. First, in laboratory and field tests, no deformation was noted radially outside 2 cm of the soil sampler. Secondly, soil directly to the side of the soil sampler is of not interest and it can be deformed excessively. However, deformations below the soil sampler could affect the sample inside the sampler.

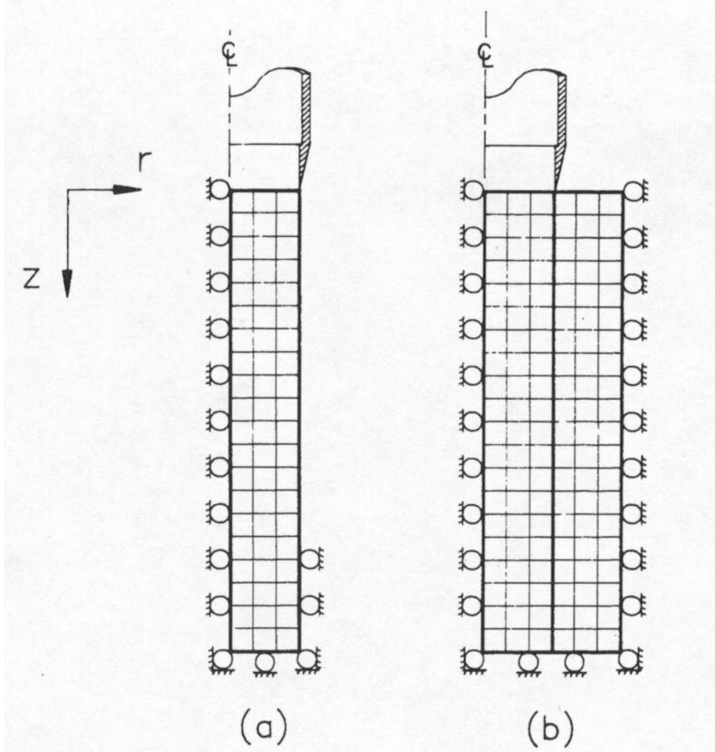

Fig. 2—Undeformed positive quadrant of axisymmetric model of (a) augered soil sample and (b) pushed soil sample with surrounding soil, showing position of soil core sampler.

Therefore, a boundary area of 5.08 cm is left beneath the soil sampler to absorb boundary affects. This extra length was also used in the laboratory experiment for this same purpose.

Load was applied to the soil core model in the form of gravity and specified displacements. The gravity load was applied to each of the models by inputting a value of wet bulk density and gravitational acceleration. Wet bulk density values were used to include the mass of water in the soil. Density values predicted by "se of the model were also wet bulk density values.

The specified displacements were also input into the finite element model of the augered soil sample. Frictional interface elements connect the soil sample to the core sampler and lie adjacent to each node (Fig. 3).

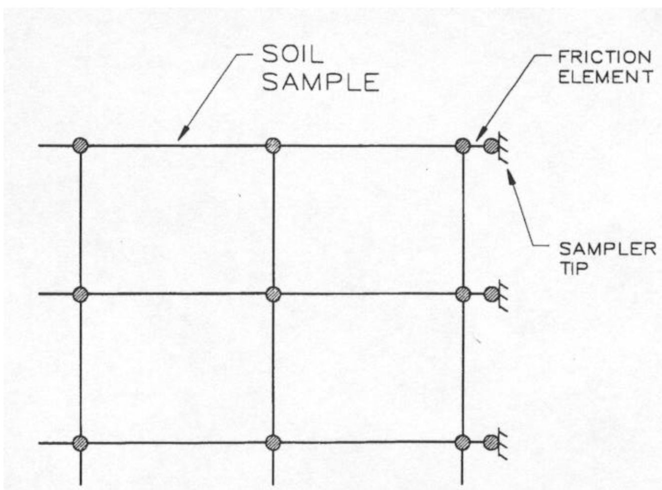

Fig. 3—Portion of cross-section of soil sample showing position of friction elements.

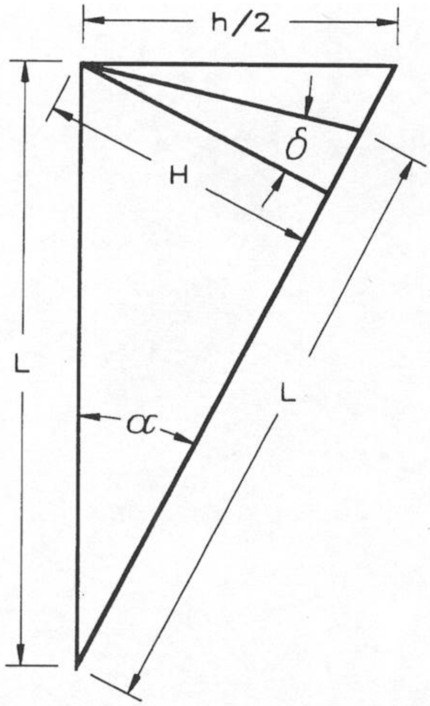

Fig. 4—Geometry of bottom half of soil sampler tip.

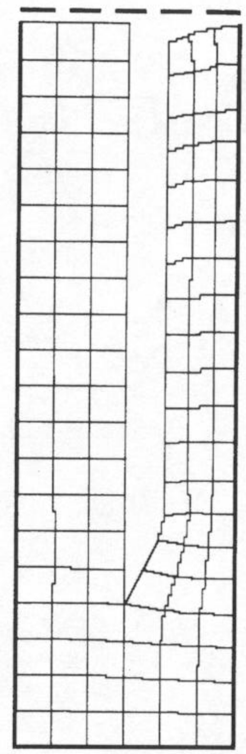

Fig. 5—Final position of soil sampler when it is incrementally moved downward into the soil mass.

After a gravity load was applied to the soil samples, the top friction element was moved down the length of one element. The stiffness matrix was saved at this point, and the load caused by displacement of the frictional element released. This friction element is now free, having no more effect on the soil sample. The next friction element downward was then moved in the same way, and the stiffness matrix again saved. This process continued until the last friction element had been moved downward. At this point, its load was removed, and the soil core was unstressed. The soil core returned to its original shape, or it exhibited plastic behavior depending upon whether or not the linear portion of the stress-strain curve had been exceeded.

Specified displacements were also used to load the soil sampler model that did not use an auger, but their form was slightly more complex. Displacements of the friction elements were handled in the same manner as before, but deformation of the surrounding soil was also considered. Fig. 4 shows the geometry of the bottom half of the soil core sampler tip that was pushed downward. If no friction was present, the soil particles moved up the soil core tip the same distance, L, as the soil sampler moved downward. But when friction was present, the distance the soil particles moved up the soil core tip was reduced. An angle was associated with this decrease and was assumed to be δ, the friction angle. From the geometry of the soil core sampler tip (Fig. 4) and trigonometric relations, the following equation was derived to determine the actual displacement of a soil particle as an angled tool passes:

$$H = \frac{L \sin(\alpha)}{\cos(\delta - \alpha/2)} \quad \ldots\ldots\ldots\ldots [1]$$

where

H = the total displacement of the soil particle, cm
L = the downward displacement of the tool, cm
δ = the friction angle, deg
α = the tool angle, deg

This equation can be split into its horizontal and vertical components for input into the model. After the tool had been displaced downward two load steps (i.e. 2L or the length of the soil sampler tip), its final position was obtained from an equation (Gill, 1968) of the form:

$$FH = \frac{h}{\cos(\alpha + \delta)} \quad \ldots\ldots\ldots\ldots [2]$$

where

h = the width of the tool, cm
FH = the final relative displacement of the soil particle, cm

Using this method of loading, the soil outside the soil sampler becomes deformed (Fig. 5) while the soil inside the sampler should be relatively unharmed. These modeling techniques seemed to reasonably simulate the soil sampling process.

Soil Parameters

Stress-strain curves were determined for a Chequest silty clay loam soil (fine, montmorillonitic, mesic, Typic Haplaquolls). This soil was split into three equal portions and wetted to three different moisture contents (15%, 18%, and 22% dry basis). The soil was then placed in large polyvinyl chloride (PVC) containers with diameter of 30 cm and depth of 35.5 cm and compressed using one of three different surface pressures (Raper and Erbach, 1985). The wet bulk densities varied among moisture contents, however, and nine different values of wet bulk density were obtained.

Soil cores were obtained from these PVC containers by using an augered soil core sampler. These cores were 7.6 cm diameter and with an approximate height to diameter ratio of 2 to 1. To obtain appropriate stress-strain curves, two replications of an unconfined compression test for each of the nine soil conditions were performed on cores in a Chatillon Universal Tester® which applied a uniform rate of deformation of 2.54 cm/min.

Unconfined compression tests were performed to obtain the stress-strain relationships due to the nature of the investigation. The soil samples that are obtained with the core sampler are in an unconfined state inside this sampler in both augered and nonaugered samplers. For both of these samplers the confining pressure is zero.

Additional soil cores of 20.4-cm length were taken from the PVC containers, split into 5.1-cm sections, and weighed to obtain their wet bulk density. A 2 x 2 factorial randomized block analysis of variance of the data was then performed. The factors were the method of obtaining the soil cores for each of the soil conditions. The core sampler used to obtain these soil cores was operated (a) with and without the aid of an auger and(b) with and without a coating of 3M TFE Lube® (a form of Teflon® or polytetrafluoroethylene).

Soil-metal friction is a very complex phenomenon. It consists of several different components (Nichols, 1925), including Coulomb or dry friction and soil-metal adhesion. The "apparent" coefficient of friction (Gill and Vanden Berg, 1968), which includes both these major components, can be calculated according to the formula:

$$\mu' = F / N \qquad [3]$$

where

μ' = the "apparent" coefficient of friction
F = the tangential force
N = the normal force

Coefficients of friction were obtained for the same Chequest silty clay loam soil. A slider was used to obtain the apparent coefficient of friction between (a) soil and metal and (b) soil and a Teflon® coated metal surface. This slider was attached to the tool bar of the soil bin located in the Agricultural Engineering Department at Iowa State University. The soil bin was then moved at a constant speed of 9.1 cm/s. A Chatillon Digital Force Gauge® was placed between the slider and the tool bar to measure the frictional forces.

For the finite element model, the tool was incremented downward by L or 1.27 cm (half the tool length). After this displacement the model iterated several times until the solution converged. The tool angle was 18.5 deg, and the tool width was 0.85 cm. The friction angles were obtained by using the coefficient of friction data, equation [3], and the formula:

$$\delta = \tan^{-1} \mu' \qquad [4]$$

where

δ = the friction angle, deg
μ' = the "apparent" coefficient of friction

To evaluate the effect of a Teflon® coating, the slider also was coated with 3M TFE Lube® Two replications of the experiment with three normal forces at all three moisture contents of soil were used to determine the coefficients of friction from equation [3].

RESULTS AND DISCUSSION

Soil Parameters

Laboratory analysis of the Chequest silty clay loam soil showed that it contained 38.4%, 33.5%, and 28.1% sand, silt, and clay respectively. It also contained 2.2% organic matter and had a specific surface of 74.53 m^2/g.

Results from the unconfined compression tests required that the low-moisture content soil be eliminated from the experiment. The correlation coefficients for these tests were extremely low, especially for the low bulk density value. Using only the 18% and 22% **moisture** content soils still enabled us to examine a wide range of friction coefficients. It was also decided to eliminate the middle bulk density values from each of the remaining moisture contents of soil. This elimination decreased the number of necessary computer runs to four but still enabled us to examine potential significant trends.

Results of the soil friction tests showed that the apparent coefficient of friction was decreased when Teflon® spray was applied to the slider. In the 18% and 22% moisture content soils, the coefficient of friction decreased 9.3%, and 5.6%, respectively (Fig. 6).

The initial slopes of the stress-strain curves were used as the moduli of elasticity (Figs. 7 and 8) for the soil surrounding the soil core in the pushed soil sampler case. Least-squares cubic equations were fitted to the data by using SAS (SAS Institute, Inc., 1982) for the data obtained from the unconfined compression tests. These equations were used to predict the stress of a soil medium under five given strains for input into the finite element program.

Finite Element Program

Table 1 was formed by using the tool geometry given earlier for the soil sampler used in this experiment. It

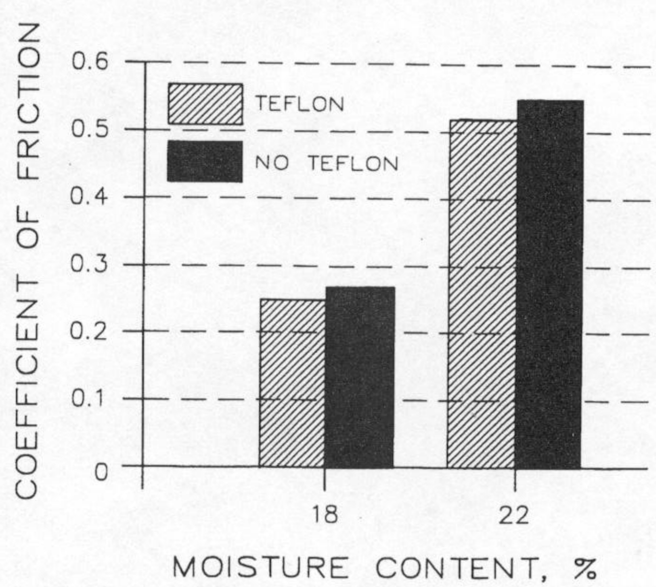

Fig. 6—Coefficients of friction for Chequest soil.

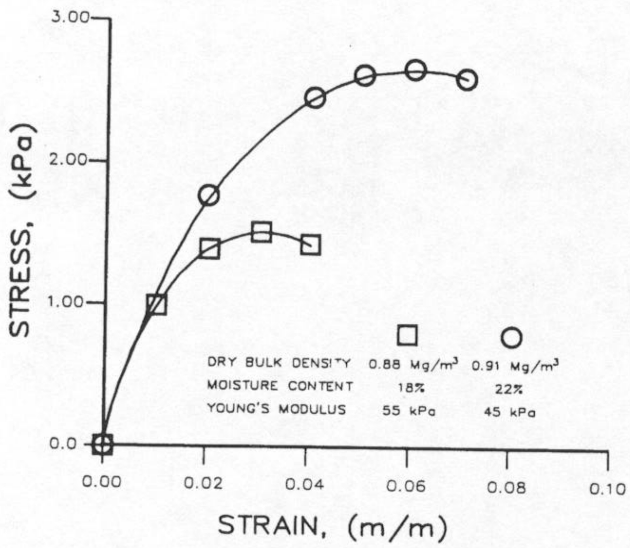

Fig. 7—Stress-strain curves for low bulk density soil.

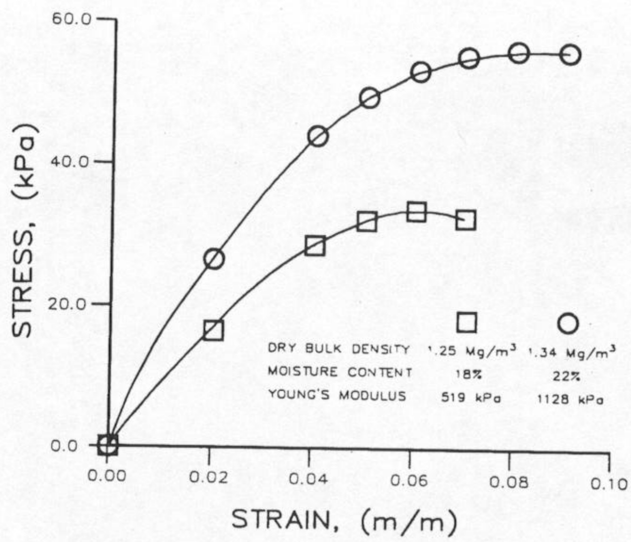

Fig. 8—Stress-strain curves for high bulk density soil.

shows the relative displacements of a soil particle, UR and UZ, when an angled tool is incrementally moved downward. The final position of the soil particle is calculated after the initial two load steps.

With use of the finite element method techniques discussed earlier to simulate movement of the soil sampler into the ground, the final displacements of each element's nodes were used to calculate a final value of wet bulk density for 2.54-cm increments downward into the soil sample. These values did not change very much despite the initial soil condition or the method used to sample. Forces generated by the sliding interface element seemed to be exceedingly small, and did not affect the bulk density of the sample significantly. They did decrease, however, as the soil sampling method changed from pushing the soil sampler into the ground to aiding the sampling process with an auger.

The mean values of wet bulk density obtained over all depths are given in Table 2, along with the measured values obtained in the laboratory. These values show that the theoretical results are slightly higher than the actual values. In the finite element model, the effect of an auger seems to reduce compaction of the soil core. The pushed sampler tends to compress the soil sample a slight amount, but its effect is minimal, even though statistically significant (p=0.00l).

Results from the laboratory experiment indicate just the opposite of the finite element method. The value of wet bulk density obtained with the auger is almost 0.05 Mg/m^3 higher than the value obtained without the auger. This difference is significant at the 10% error level. The auger seems to compact the soil sample. or the lack of an auger seems to loosen the soil sample. Further analysis was required before a conclusion could be drawn.

TABLE 2. WET BULK DENSITY VALUES FOR FINITE ELEMENT MODEL AND MODIFIED LABORATORY EXPERIMENT AVERAGED OVER MOISTURE CONTENTS AND DEPTHS

	Predicted	Measured
	Mg/m^3	
Sampler		
Augered	1.3197	1.276
Pushed	1.3215	1.230
LSD (0.10)	0.0001	0.044
Coating		
No Teflon®	1.3206	1.268
Teflon®	1.3206	1.238
LSD (0.10)	0.0001	0.044

In the finite element model, Teflon® had no effect (Table 2). This lack of a trend indicated that the coefficient of friction had little effect on the bulk density of the soil sample. In the laboratory experiment, however, somewhat smaller values of bulk density were obtained by using a Teflon® coating. This effect was less than 0.03 Mg/m^3 and was not significant, even at the 25% error level.

The initial bulk density could not be held constant and changed between treatments and between replications

TABLE 1. SOIL PARTICLE DISPLACEMENTS WHEN AN ANGLED TOOL IS MOVED DOWNWARD

Friction angle	Load step 1 UR	Load step 1 UZ	Load step 2 UR	Load step 2 UZ	Final position UR	Final position UZ
deg	cm					
14.10	0.3713	−0.1603	0.7426	−0.3205	0.8500	−0.5435
15.48	0.3682	−0.1696	0.7364	−0.3391	0.8500	−0.5728
27.53	0.3399	−0.2541	0.6798	−0.5083	0.8500	−0.8812
28.90	0.3365	−0.2643	0.6730	−0.5286	0.8500	−0.9243

TABLE 3. INDEX OF COMPACTION VALUES FOR FINITE ELEMENT MODEL AND MODIFIED LABORATORY EXPERIMENT AVERAGED OVER MOISTURE CONTENTS AND DEPTHS

	Predicted	Measured
	——————— %	——————
Sampler		
Augered	−0.1591	0.338
Pushed	−0.3079	2.512
LSD (0.10)	0.0119	2.210
Coating		
No Teflon®	−0.2324	0.161
Teflon®	−0.2346	2.689
LSD (0.10)	0.0119	2.210

due to the variability of the soil and its changing moisture content. To better understand the effects of the treatments, an index of compaction (Vazin, 1982) was used to examine the data. The index of compaction is defined as:

$$IC = 100 * (Ibd - Fbd)/Ibd \quad \ldots\ldots\ldots\ldots\ldots\ldots [5]$$

where

IC = the index of compaction, %

Ibd = the initial wet bulk density of the soil, Mg/m^3

Fbd = the final wet bulk density of the soil, Mg/m^3

The index of compaction eliminates differences due to the initial condition's and evaluates the experiment only through a percentage change. Values of the index of compaction near zero show there was little sample disturbance. Negative values were expected in cases where compaction occurs. Positive values would indicate a decrease in the bulk density. Large absolute values of the index of compaction would indicate that the soil sample was unacceptable.

Compaction indexes were averaged across treatments and depths predicted by the finite element model and measured in the laboratory experiment (Table 3). The indexes for the finite element results are all less than 0.5% and show very little compaction taking place. Excessive disturbance is shown by the positive compaction indexes greater than 2.5% for the laboratory results. Therefore, predicted wet bulk density of the soils used in this experiment could decrease from 0.02 to 0.04 Mg/m^3. These indicate significant sampling errors when either a soil sampler was used without an anger or when the soil sampler tip was coated with Teflon®.

Differences in results obtained with the finite element method and the laboratory tests could result from significant tension forces that developed near the soil sampler tip. These forces could cause excessive shearing of the soil sample near the sampler tip and could reduce the bulk density of the soil in that area. An analysis of the finite element results showed that the wet bulk density values in this area were somewhat lower than the original values of wet bulk density but were overshadowed by compaction of the centermost elements at this same level. Failure of the finite element method to take into consideration the granular nature of soils and its failure planes could have caused this inaccuracy.

The finite element model also showed that reducing the coefficient of friction by applying Teflon® to the soil sampler tip has little effect on wet bulk density. Analyzing the laboratory tests with the compaction index showed, however, that using Teflon® decreased the wet bulk density values and disturbed the soil sample. This expansion of the soil samples could be more detrimental than a small amount of compaction.

CONCLUSIONS

The following conclusions can be drawn from this research:

1. The finite element method was reasonably able to model the soil for compressive cases. but in situations where it seemed that soil shear was significant, the model proved unsatisfactory.
2. Experimental and finite element results indicate that the measurement accuracy of soil bulk density can be maximized by using an auger to remove outside soil as a soil sampler is pushed into the ground.
3. Experimental and finite element results indicate that coating the soil sampler tip with Teflon® does not significantly decrease soil sample compaction.

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